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A monochromatic x-ray imaging system for characterizing low-density foams

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In High Energy Density (HED) laser experiments, targets often require small, low-density, foam components. However, their limited size can preclude single component characterization, forcing one to rely solely on less accurate bulk measurements. We have developed a monochromatic imaging a system to characterize both the density and uniformity of single component low-mass foams. This x-ray assembly is capable of determining line-averaged density variations near the 1% level, and provides statistically identical results to those obtained at the Brookhaven's NSLS. This system has the added benefit of providing two-dimensional density data, allowing an assessment of density uniformity.

I. INTRODUCTION

In many High Energy Density (HED) experiments, achieving the appropriate hydrodynamic or radiative scaling often requires the use of sub-millimeter sized, low-density, foams. Unfortunately, characterizing the density of these components can be particularly challenging. Their limited mass leads to large uncertainties when traditional gravimetric measurements are employed. Using high-energy broadband radiography can be very effective at identifying non-uniformities within a component, but large uncertainties in source spectrum make determining absolute density unrealistic.

In this paper, we introduce a monochromatic imaging system that accurately quantifies the x-ray transmission through single component low-density foam samples. Once the foam dimensions are measured, the monochromatic cold opacity can be assumed, and a two-dimensional image of the line-averaged density can be inferred. The x-ray assembly is capable of determining line-averaged density variations near the 1% level, and provides statistically identical results to those obtained using Brookhaven's NSLS. In the following sections we examine the theory behind the monochromatic x-ray assembly, present its principal components, and discuss the calibration and error quantification efforts.

II. THEORY

The monochromatic x-ray assembly provides a high precision measure of the relative x-ray transmission through target sample. If the thickness and atomic concentrations of the target sample are known, then the line-average density can be extracted. The relationship between transmission and density can be derived from Equation 1, which describes the change in intensity as light passes through an absorptive media.

$$dI(\nu,z) = -K(\nu)\rho(z)I(\nu,z)dz \qquad (1)$$

In Equation 1, which has been simplified to describe an infinite planar problem, I is the intensity, K the opacity at frequency ν, and ρ is the density at depth z. Assuming a uniform intensity field incident on the material, it can be shown that the intensity at depth z is described by

$$I(\nu,z) = I_o(\nu)e^{-K(\nu)\bar{\rho}z}. \qquad (2)$$

For a monochromatic source, $\nu \rightarrow \nu_o$, the integrals simplify greatly and the line-average density becomes

$$\bar{\rho} = -\ln T(\nu_o)/K(\nu_o)z. \qquad (3)$$

Although Equation 3 relates line-averaged density to transmission, opacity, and thickness, these parameters cannot be known to infinite accuracy. It is important to assess how uncertainties in T, K, or z propagate through to the interpretation of the density. This can be accomplished by conducting a Taylor expansion on Equation 3 appropriately summing the variances, see Equation 4.

$$\sigma_\rho^2 = \left|\frac{1}{T(\nu_o)K(\upsilon_o)z}\right|^2 \sigma_T^2 + \left|\frac{\ln T(\nu_o)}{zK(\nu_o)^2}\right|^2 \sigma_K^2 + \left|\frac{\ln T(\nu_o)}{K(\nu_o)z^2}\right|^2 \sigma_z^2 \quad (4)$$

In general, the spatial dimensions of foam component are known to an accuracy of 1-2 microns (σ_z ~ 1-2E-4 cm). The cold opacities used in the work were obtained from the Center of X-ray Optics website. An error of 1% (σ_K/K ~ 0.01) is assumed. However, the opacity acts scalar parameter, so any error in this assumption only modifies the accuracy of the inferred absolute density and not the component-to-component precision. In other words, the error in the true density of a particular component may be large but the error in relative density between two samples will be very small. Since this work is focused solely on SiO_2 foams at 5.415 keV, the cold opacity is assumed to be 108.8 cm^2/g. The magnitude of σ_T will be discussed in Section IVA.

III. MONOCHROMATIC X-RAY ASSEMBLY

Manufactured by XOS, a DCC X-Beam with a chromium anode served as the x-ray source. However, the original germanium toroidal optic that came with the source was insufficient to provide a uniform illumination pattern. A closer examination showed that the stresses from mounting the thin germanium led to striations in the optic, resulting in large amplitude peak-valley variations in the image plane. To overcome this, a concave germanium (111) crystal was employed. The assembly, shown in Figure 1, was vertically aligned to allow target components to rest directly on the beryllium filter, thus removing the need for any complicated mounting fixture. Imaging is accomplished with a PIXIS-XO 2048B CCD camera.

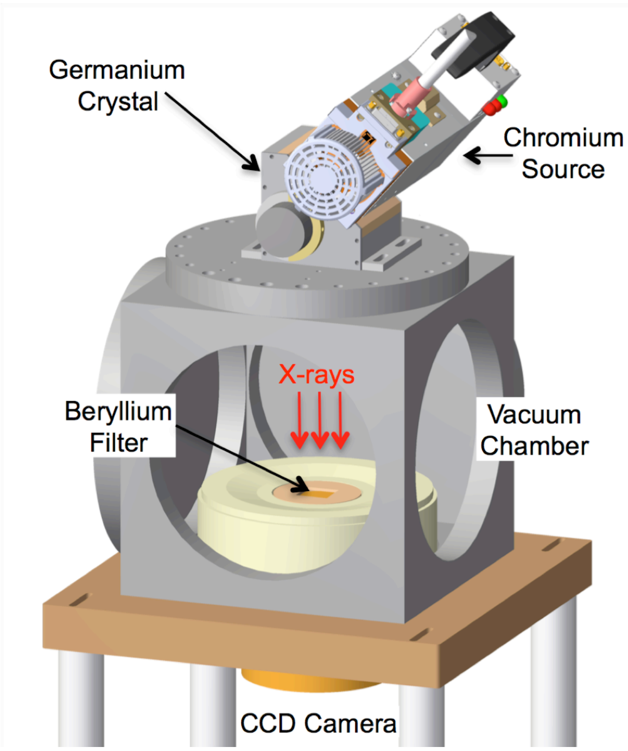

FIG. 1. A germanium crystal configured to select chromium $K\alpha$ (5415 eV) directs a monochromatic x-ray beam onto the imaging CCD camera. Multiple images are averaged together providing a two-dimensional, low noise image of the target component.

Although 13.5-µm-square pixel size of the PIXIS camera is significantly larger that the resolution that can be obtained by film, using the CCD camera in accumulation mode allowed hundreds of images to be acquired and averaged together. Moreover, operating in this mode completely bypassed problem with camera saturation, which showed that the optimum exposure duration was about 250 ms. All subsequent data presented below are 250 frame ensembles.

IV. CHARACTERIZATION TESTS

To establish confidence in the x-ray assembly data, two additional efforts were required. The first, discussed in Subsection A, involved understanding the experimental uncertainties within the transmission measurement. After that, x-ray assembly data needed to be compared with similar data obtained from a well-characterized monochromatic source. For this purpose, we chose to utilize Brookhaven National Laboratory's National Synchrotron Light Source (NSLS). Those results are summarized in Subsection B.

A. Transmission Error Assessment

The experimental error in the x-ray transmission measurement (σ_T) is dominated by the photon statistics. Figure 2 shows the x-ray transmission through a ~125 mg/cc, 2-mm diameter, 200-micron thick, SiO_2 foam for a variety of ensembles sizes.

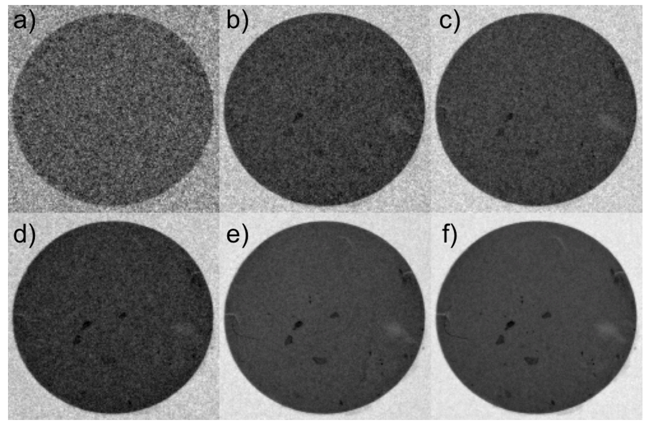

FIG. 2. Data showing the enhanced resolution achieved with greater photon statistics. The above are ensembles over a) 1, b) 5, c) 20, d) 50, e) 100, f) 250 frames.

The pixel-to-pixel uncertainty for the 250-frame ensemble is shown in Figure 3. Two regions of interest were selected, the background (blue), and a smaller area of the foam (red). The histograms are plotted on the left. The data show that the pixel-to-pixel variation (σ_T) is of order 1%. However, if 13.5-micron resolution is not required, averaging multiple pixels together reduces this variation by $1/\sqrt{pixel\ \ number}$. Thus the variation between 67-micron regions would be only 0.2%. At this point, uncertainties in thickness and opacity completely dominate.

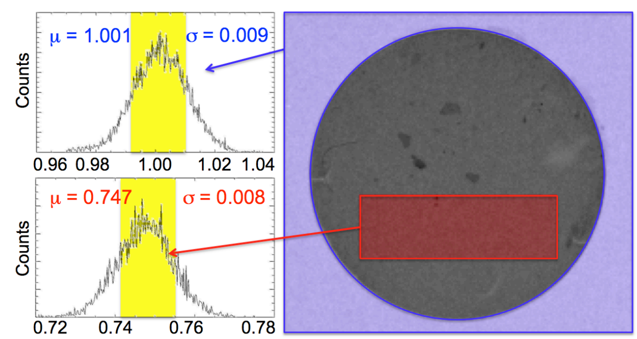

FIG. 3. Analysis of the 250-frame average (right) shows the 1σ pixel-to-pixel variation for the background (top left) and sample (bottom left) is about 1%. Averaging over larger regions-of-interest can reduce this uncertainty further.

B. NSLS Comparisons

Using a 15-µm thick pure silicon wafer as our standard, the transmission at 5.415 keV was measured on the x-ray assembly and compared with the results from NSLS. The data, shown in Table 1 were statistically identical.

	X-ray Assembly	NSLS
Transmission @ 5.415 keV	59.4 ± 0.8 %	59.0 ± 0.5 %

TABLE. 1. Transmission measurements for the Silicon standard.

In addition, four SiO_2 foams were characterized on both the x-ray assemble and at NSLS. The foams were only 400 microns in diameter so the 1/128-inch (198 µm) beam diameter was used. Once aligned, each sample was positioned to maximize the throughput of the beam. With the transmissions measured at both facilities, the assumed thickness and opacity were 400 µm and 108.8 cm^2/g respectively. The results, summarized in Figure 4, were identical. This data supports the conclusion that the x-ray assembly predominately monochromatic and any second order contamination appears to have a negligible impact.

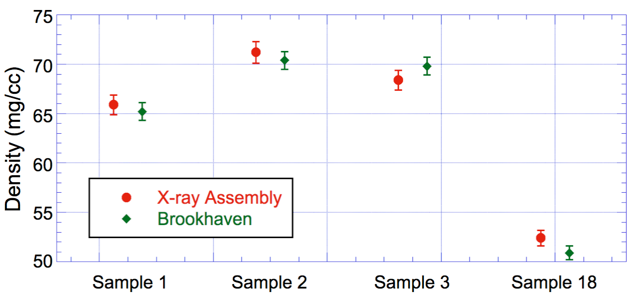

FIG. 4. Densities inferred with the x-ray assembly are statistically equivalent to measurements made at Brookhaven's NSLS.

IV. DOUBLE-BLIND STUDY

Manufacturing HED targets that are scientifically informative requires the ability to both produce a component with a desired specification and to be capable of identifying when a given specification is not met. With this in mind, a double-blind study was performed. A series of samples with three different densities were produced. The sample foams were cylindrical with both height and diameter equaling 400 µm. This size is similar to many HED target requirements but it is too small for accurate gravimetric measurements. As a result, larger "witness" foams were made and their bulk densities were measured. Each sample was characterized using the x-ray assembly. The results are summarized in Figure 5.

With the exception of the high-density case (Figure 5a), the bulk density assessments differed significantly from the target samples that were actually produced. This is very informative since, without the ability to perform gravimetric measurements on individual components, the bulk assessment is often the only option in quoting a manufactured specification. These results bring into question the legitimacy of using bulk assessments when using cast in place foams.

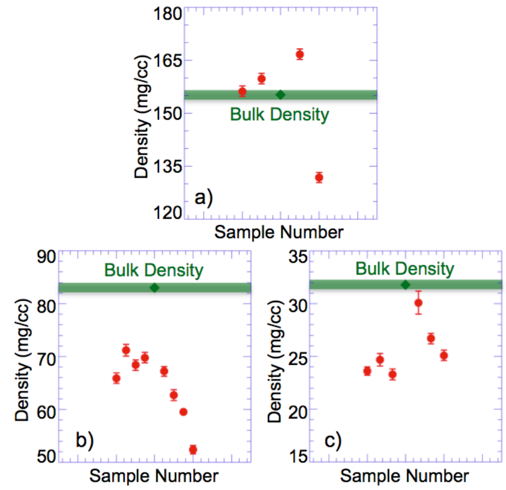

FIG. 5. The double blind results showing the bulk density often differs significantly from individual samples. However, the x-ray assembly can easily discern these deviations.

During the course of this study, an interesting trend emerged. The inferred density seemed to increase with time. It was postulated that this resulted from water absorption and a set of samples were baked over three days and subsequently measured again. After baking, the density fell, approaching their original values (Figure 6). This particular effect will require more study as target foams are machined, assembled, shipped, and employed at the laser facility, it is impossible to eliminate all exposure to water.

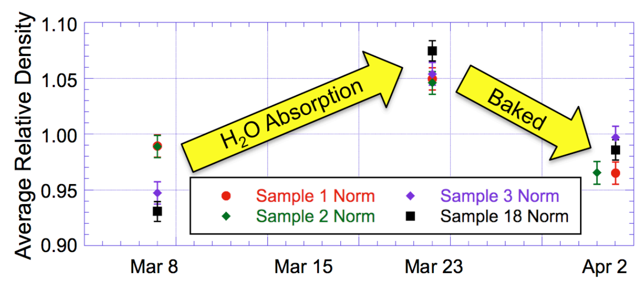

FIG. 6. X-ray assembly data showing the hygroscopic nature of SiO_2 foams. Increased water content can lead to higher inferred densities if not properly accounted for. After baking, the densities approach their original values.

V. SUMMARY

We have developed a monochromatic imaging a system to characterize both the density and uniformity of single component low-mass foams for use in HED laser targets. The x-ray assembly is capable of determining line-averaged density variations near the 1% level, and provides statistically identical results to those obtained at the Brookhaven's NSLS. During a series of blind tests, the x-ray assembly data clearly discerned sample-to-sample deviations of 1%. Moreover, this data also show that the bulk density witness samples are not always representative of smaller cast-in-place foams.

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